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Forest Service
Equipment
Development
Center

Project Report
8522 1201

2200—Range

San Dimas, CA

February 1985

# Range Water Pumping Systems

## State-of-The-Art-Review

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# Range Water Pumping Systems

## State-of-The-Art-Review

*by*

Dan W. McKenzie—*Mechanical Engineer*
Forest Service
Equipment Development Center
San Dimas, California

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CONTENTS

# ILLUSTRATIONS

## INTRODUCTION

The goals of the Range Water Systems Improvements project are to improve range water supplies and systems for pumping and handling range water. The objectives, as determined by the Structural Range Improvements Workgroup of the Vegetative Rehabilitation and Equipment Workshop, are to:

1. Investigate and develop systems for inhibiting or preventing stock watering tanks from freezing.

2. Investigate and develop solar water pumping systems as alternatives to the conventional windmill.

This Project Record is a "state-of-the-art" review of information learned from the investigative effort conducted in the solar water pumping systems portion of the Range Water System Improvements project.

The Range Water Systems Improvements project is very timely because of the amount of ongoing research and development work in water pumping and the new equipment and techniques becoming available. The conventional windmill is a functional, reliable, long-lasting, economical range water pumping system. Functional and economical alternatives are not easy to develop. However, some of the new water pumping equipment and also equipment now under development (under some circumstances) have the potential to be cost-effective alternatives to the conventional windmill.

Three categories of equipment may offer alternatives to the conventional windmill:

1. Improved or new windmills.
2. Photovoltaic-powered pumping systems.
3. Solar-thermal pumping systems.

In the improved and new windmill and photovoltaic categories, considerable research and development are also underway with new equipment and also promising new equipment being developed. In the solar-thermal category, demonstration equipment is still being operated, but little, if any, new equipment is being produced.

## IMPROVED OR NEW WINDMILLS

The conventional multibladed windmill—a functional, reliable, long-lasting, economical range water pumping system—has been in use for over 125 years. During this time, the windmill has undergone continual product improvement—such as backgearing for deeper pumping and smoother operation; enclosed gearing requiring oiling annually instead of weekly; improved sail construction and design; and improved automatic regulation—and is therefore not an easy product to improve or replace. However, work continues on improvements to the conventional windmill and the development of new designs such as:

1. Fully counterbalanced windmill
2. Spring-counterbalanced windmill
3. Cam-operated windmill
4. Hydraulic system which replaces the pump rods of a conventional windmill
5. Automatic stroke control for a conventional windmill
6. Automatic stroke control for a three-bladed wind turbine
7. Electric wind ac generator driving an ac submersible pump
8. Electric wind dc generator driving a dc submersible pump
9. Windmill-driven air compressor operating an air lift pump
10. Long-life well cylinder
11. Performance modeling and testing of windmills.

### Fully Counterbalanced Windmill

In a fully counterbalanced windmill, one-half the pumping work is done on the upstroke and one-half on the downstroke. On an uncounterbalanced windmill, all the pumping work is done on the upstroke plus also lifting the pump sucker rods. Fully counterbalancing a windmill allows the windmill to start and then pump water at lower windspeeds than a windmill that is not counterbalanced.

In a fully counterbalanced windmill, all the weight of the pump rods, one-half the water weight, and one-half the friction forces in the pump and stuffing box are counterbalanced by counterweights. This results in the starting torque being reduced to about 33 percent (with a 1-7/8-in cylinder, 3/4-in, airtight, hollow-steel rod, and assuming a pump mechanical efficiency of 70 percent) as compared to an uncounterbalanced windmill. The torque developed by a windmill is approximately proportional to the square of the windspeed. If a fully counterbalanced windmill will start in a 7 mph wind, it will take a 12.2 mph wind to start a conventional or uncounterbalanced windmill.

In an extensive test of a fully counterbalanced windmill and an uncounterbalanced windmill set side-by-side (75 ft apart) on the Navajo Indian Reservation near Window Rock, AZ, the fully counterbalanced windmill pumped

substantially more water (13 times) at windspeeds below 10 mph than the conventional (uncounterbalanced) windmill; and at windspeeds above 10 mph, 32 percent more water was pumped by the fully counterbalanced windmill.

A fully counterbalanced windmill is available, in a 21-ft size only, from the Wind Baron Corporation, 3702 West Buckeye Road, Phoenix, AZ 85009, telephone (602) 269-6900 (see figs. 1 and 2).

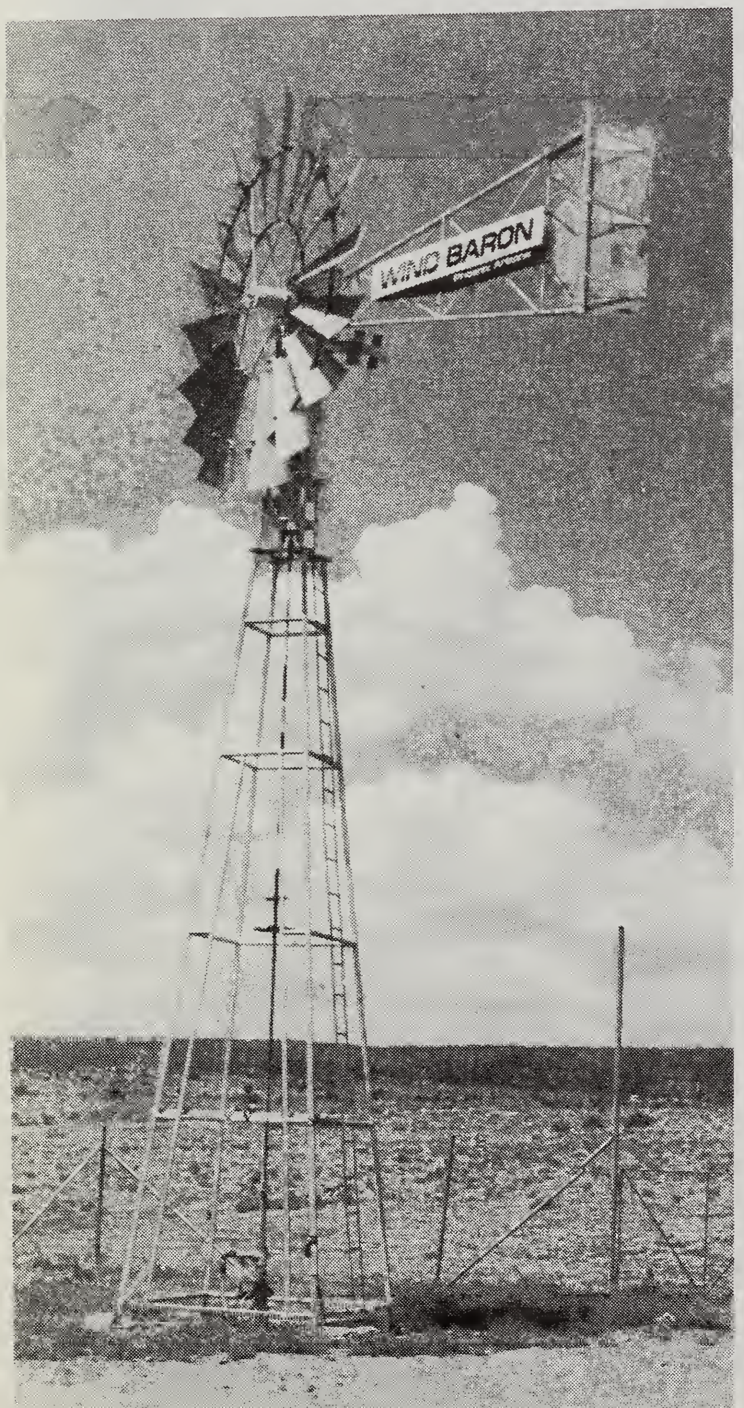



*Figure 1.—Fully counterbalanced windmill operating on the Navajo Indian Reservation near Window Rock, AZ.*


*Figure 2.—Weights and weight arms of fully counterbalanced windmill.*

## Spring-Counterbalanced Windmill

The Bureau of Land Management (BLM), Vale District, OR, has developed a method of spring counterbalancing conventional multibladed windmills so they will start and run at lower wind speeds. Extension springs, 48-in in length and 2-in in diameter, are attached at the top of the tower and the free end is connected to the pump pole or red rod (see figs. 3 and 4). Up to four springs have been used when a windmill is pumping a deep well. The Vale District uses a scale made from a hydraulic cylinder and pressure gage to determine the upstroke and downstroke loadings. The upstroke loading is the total weight of the pump rods, water column, and friction forces. The downstroke loading is the weight of the pump rods minus a small friction force. The counterbalance needed is the downstroke loading plus one-half the difference between the downstroke and upstroke loadings. The number of springs required can now be determined (generally two to four) in that each spring will counterbalance about 100 lb. The springs are hooked to the tower near the top. A bracket is attached to the pump pole to which the free end of the springs are hooked. The springs used by the Vale District are from a New Holland bailwagon (1046 or 1048), part number 510397, costing approximately $64 each.

On the Aermoter windmills, the Vale District also replaces the main support friction bearing on which the millhead rests with a roller bearing so the mill will turn more easily and face into a light wind. On the Dempster windmill, the main support bearing does not have to be replaced because it is already a ball bearing. Spring counterbalance in excess of three-quarters of the weight of the windmill should not be used.

*Figure 3.—Spring-counterbalanced windmill in operation near Vale, OR.*

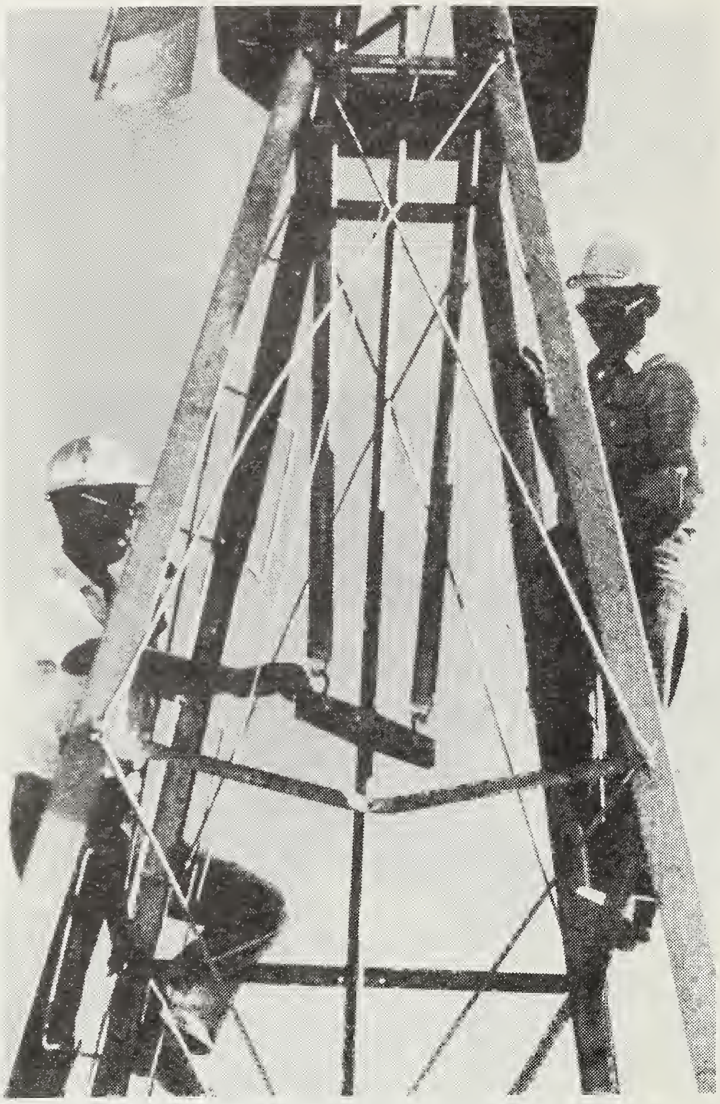


*Figure 4.—Springs being installed for spring counterbalancing a windmill.*

The approximate weights of windmills are:

| Size (ft) | Weight (lb) | Three-quarters of weight (lb) |
|---|---|---|
| 6 | 215 | 160 |
| 8 | 370 | 275 |
| 10 | 665 | 500 |
| 12 | 1,130 | 847 |
| 14 | 1,781 | 1,300 |
| 16 | 2,508 | 1,800 |

A frequent concern and comment made about the BLM Vale method of spring counterbalancing is that the conventional windmill is not designed to take loading on the downstroke and, if a windmill is loaded on the downstroke, accelerated and unusual wear will result.

In normal operation, windmills are loaded on the downstroke (the weight of the pump rods) and the Vale District reports no accelerated or unusual wear.

### Cam-Operated Windmill

In a cam-operated windmill, the lift cam is designed so the time of the lift stroke is longer than the time of the down or return stroke. When a cam mechanism is used in a windmill, the starting torque is reduced allowing the windmill to start pumping water at lower windspeeds than a conventional windmill. In a cam-operated windmill with three-quarters of the pumping cycle time used in the lifting stroke, and one-quarter pumping cycle time used for the return stroke, the starting torque is reduced to 42 percent (with 1-7/8-in cylinder, 3/4-in airtight, hollow-steel rod, and assuming a pump mechanical efficiency of 70 percent) of the starting torque of a conventional windmill. If all of the sucker rod weight were counterbalanced, the starting torque would be

reduced to 28 percent of the torque required to start a conventional windmill. However, on a cam-equipped windmill, the sucker rod cannot be 100 percent counterbalanced. If the sucker rod were 100 percent counterbalanced, it would not return. If it is possible to counterbalance up to 70 percent of the sucker rod, the starting torque would be reduced to 32 percent. As the torque developed by a windmill is approximately proportional to the square of the

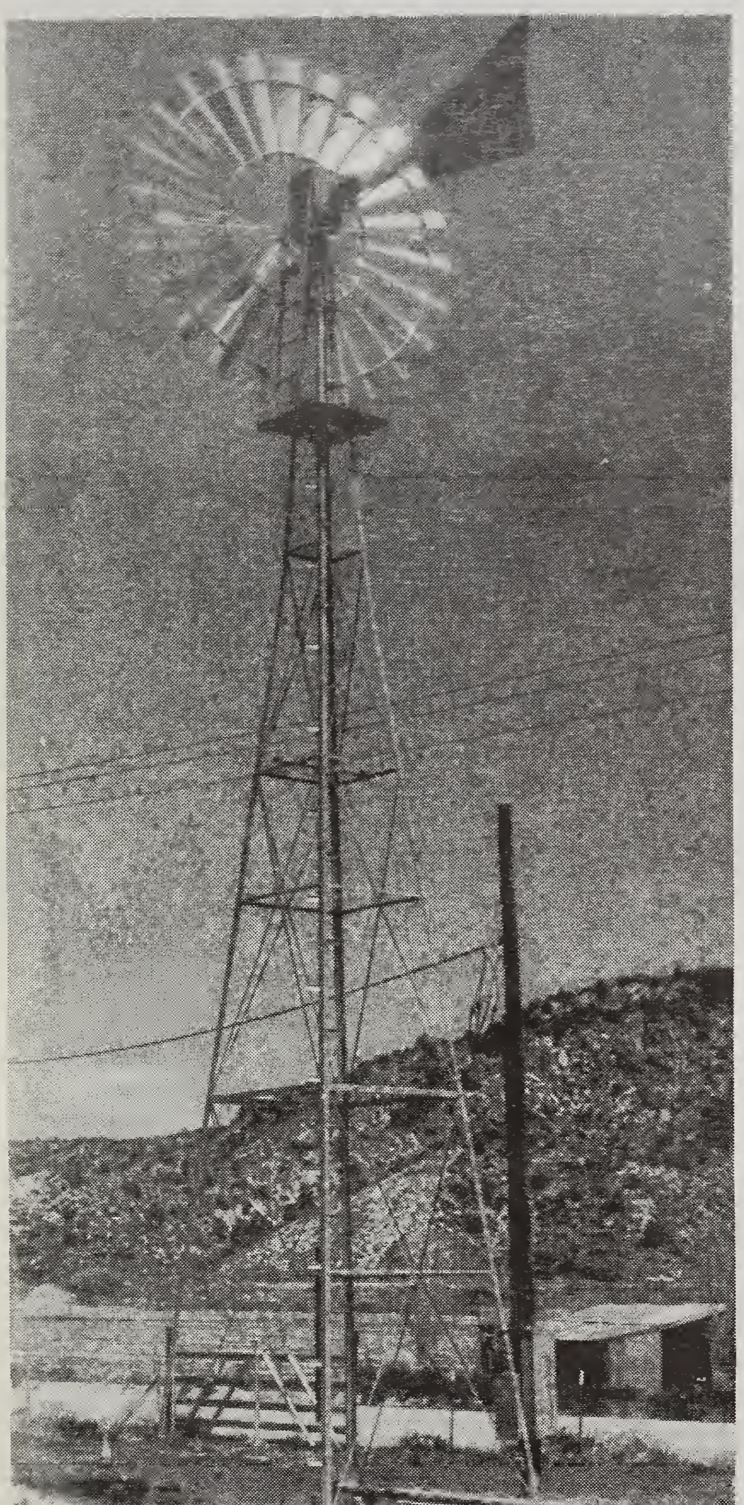


*Figure 5.—Cam-operated windmill.*

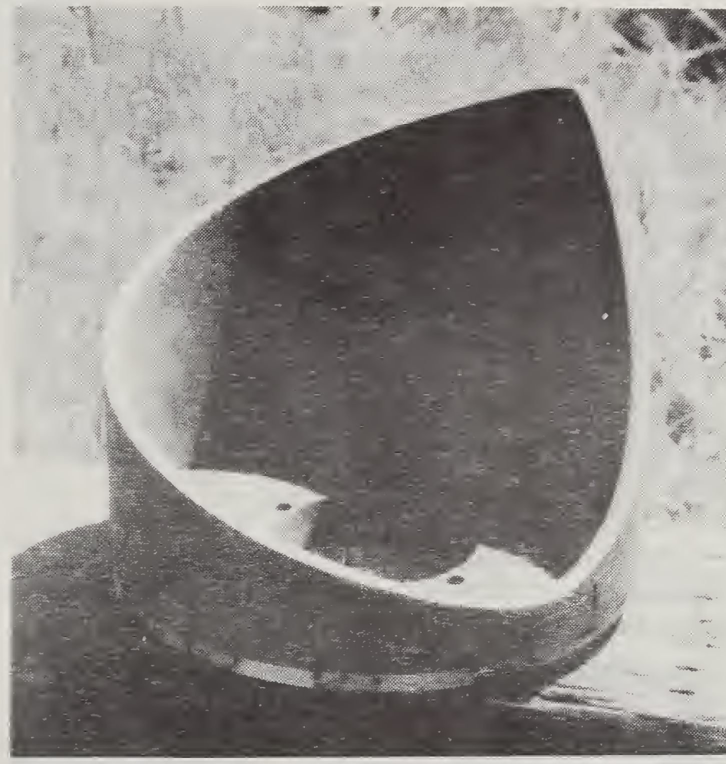


*Figure 6.—Cam of cam-operated windmill with a three-quarters lift time and a one-quarter return of downstroke time.*

windspeed, and if a cam-operated windmill with a three-quarter lift time cam and 100 percent counterbalanced will start in a 7 mph wind, it will take a 10.8 mph wind to start a conventional windmill. If 70 percent of the sucker rod weight were counterbalanced, and the cam windmill will start in a 7 mph wind, it would take a 12.4 mph wind to start a conventional windmill. At windspeeds above starting windspeed where both the cam and conventional windmill are operating well, performance will be about equal. Limited production models of cam-operated windmills have been produced by Wind Energy Unlimited, Incorporated, 2527 North Carson Street, Suite 205, Carson City, NV 89702, telephone (702) 883-9303 or (805) 248-6023 (see figs. 5 and 6).

### Hydraulic System to Replace Pumping Rods

A Texas firm is developing a hydraulic system to replace the pumping rods of a conventional windmill. The windmill is connected to a well-type cylinder located at ground level. The output of this well cylinder (water under pressure) is pumped down the well to operate a cylinder pump. The advantages seen for this hydraulic system are:

1. The water source does not have to be directly below the windmill.

2. It is lightweight and can be quickly removed from a normal depth (100 to 200 ft) well by hand.

3. The unit will start and pump water in lighter winds than a conventional sucker-rod windmill. The reason given for being able to start and pump water in lighter winds is because the windmill does not have to lift the weight of the sucker rods on the first stroke; however, due to the mechanical efficiency (force efficiency) of about 70 percent for each of the two additional well-type cylinders in the power train, they may well negate the advantage of eliminating the sucker-rod weight.

4. The design is such that wind powered water pumping can be assisted by or entirely powered by solar cells.

For more information, contact W. L. Hydraulics, 10203 Kotzebue, Suite 112, San Antonio, TX 78217, telephone (512) 654-1412.

*Figure 7.—Conventional windmill equipped with automatic stroke control device.*

*Figure 8.—Automatic stroke control device for conventional windmill.*

## Automatic Stroke Control for Conventional Windmills

The power in the wind is approximately proportional to the cube of the windspeed. However, the conventional rod and cylinder pump used on the conventional windmill can only absorb power approximately proportional to a direct function of the windspeed when in the windmill operating range. If the pumping mechanism could absorb power approximately proportional to the cube of the windspeed, the windmill would pump much more water.

Mechanical Engineering Professor Emeritus Don Avery of the University of Hawaii has developed and validated an automatic stroke control device for use with a conventional windmill (see figs. 7 and 8) which allows the windmill pump to absorb power approximately proportional to the cube of the windspeed. This device automatically changes the stroke of the well cylinder to match the level of energy in the wind (the length of the pump stroke is changed proportional to windspeed squared). This results in the volume of water pumped in relation to windspeed following approximately the same cubic relationship as the level of energy in the wind.

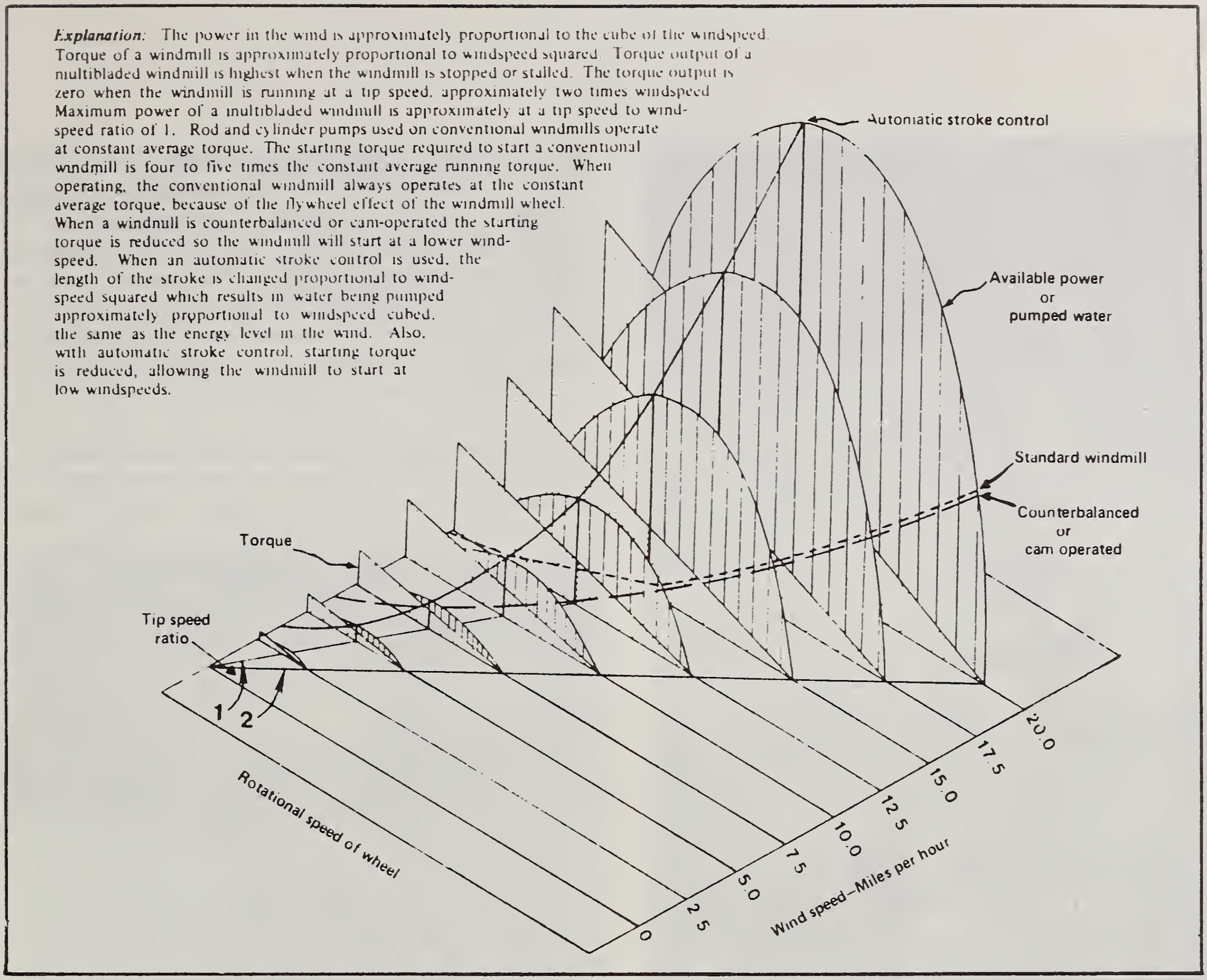



*Figure 9.—Relationship of windspeed, water pumped, available power, torque, rotational speed of wheel and tip speed to windspeed ratio of a multiblade windmill with and without a stroke control device.*

If the windspeed doubles, theoretically eight times more water will be pumped, or four times more water than a conventional windmill without a stroke-control device. Actually, water pumped is somewhat less than four times because the water pumped by a windmill without a stroke-control device is proportional to approximately one and one-quarter times windspeed, and for a windmill with a stroke control, the water pumped will be less than proportional to the cube of the windspeed because of losses in the system and limits on maximum operating torques of the windmill. Nevertheless, a greater amount of water will be pumped with a windmill equipped with a well-functioning stroke-control device than a windmill without (see fig. 9). Computer studies done by Volunteers in Technical Assistance (VITA) indicate about twice as much water can be pumped with a windmill with a stroke control as a windmill without a stroke control or the windmill can be one-half the size when equipped with a stroke-control device as compared to a windmill not equipped with a stroke-control device.

This would result in a windmill cost reduction of about one-third or more, even when adding in the cost of a stroke-control device. Also, a windmill equipped with a stroke-control device will also start and pump water at lower windspeeds than a conventional windmill without a stroke-control device. The stroke-control device that Professor Avery has developed and validated will vary the stroke from 3 to 16 in. Discussions are underway for the manufacture of the device as a kit for conventional windmills. For more information, contact Don Avery, 45-437 Akimala Street, Kaneohe, HI 96744, telephone (808) 247-1909.

## Automatic Stroke Control for a Three-Bladed Wind Turbine

Professor Avery of the University of Hawaii has also developed and validated an automatic stroke-control device for a three-bladed electric generating-type wind turbine. The development model used a 23-ft diameter rotor and the stroke will vary from 0- to 27-in (see fig. 10). The

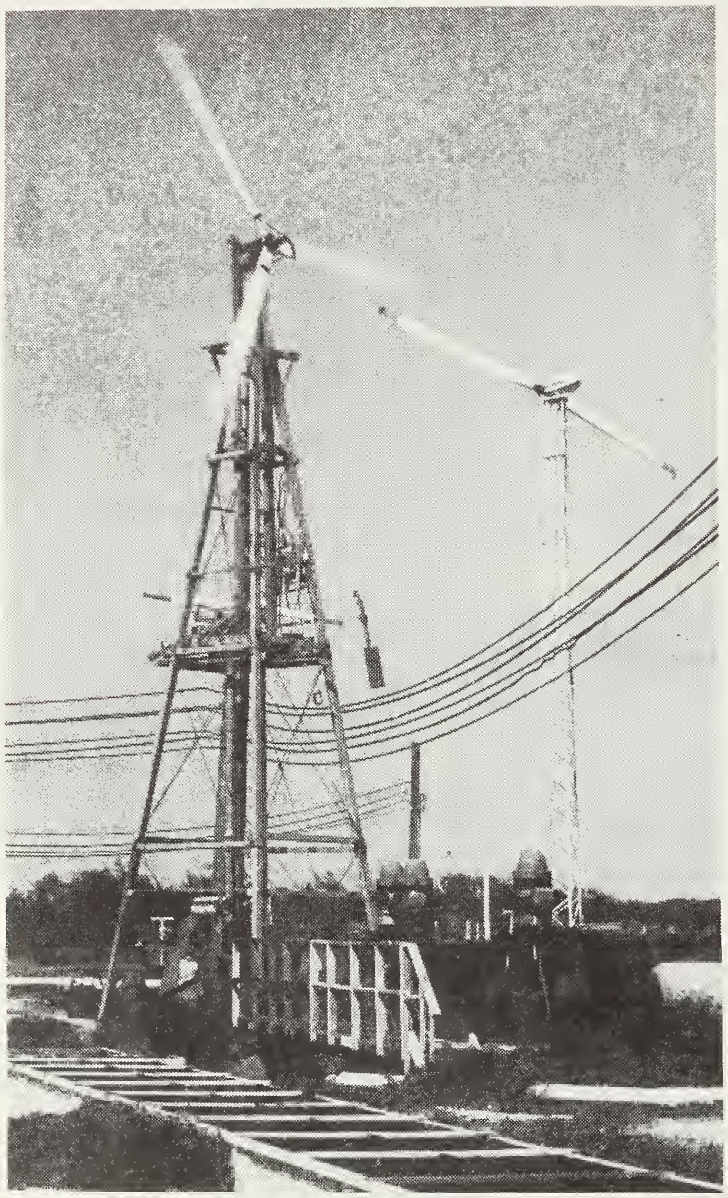


*Figure 10.—Three-bladed wind turbine equipped with automatic stroke control device.*

advantage of this device over the device developed for the conventional windmill is that a more efficient (30 percent for conventional windmills and about 40 or 45 percent for a three-bladed wind turbine) and less costly wind turbine can be used because stroke will go to zero, allowing the three-bladed wind turbine to start.

## Electric Wind AC Generator Powering an AC Submersible Pump

The USDA-ARS at the Conservation and Production Research Laboratory, Bushland, TX, is investigating the coupling of an ac submersible centrifugal pump directly to an ac wind generator to operate as a stand-alone water pumping system. They have conducted laboratory tests that show the system to be very promising. The advantages seen for this water pumping system would be lower initial cost and reduced maintenance. The reason for the potential for lower initial costs are that electric wind generators are lighter, smaller, and made with less parts than the multiblade farm-type (conventional) windmills. The reason the two- or three-blade wind turbine can be made smaller is that it operates at a higher efficiency than a multiblade farm-type windmill (about 30 percent for the multiblade, and 40 to 45 percent for the two- or three-blade wind turbine).

Also, the pump system used with the wind turbine may be able to extract more power from the wind turbine than the pump system used with the multiblade windmill. The system should require less maintenance because of the use of a down hole, submersible pump in place of conventional pump rods and well cylinder. Components to assemble an electric wind generator driving an ac submersible pump are commercially available; however, methodology for matching components is not understood or available.

Rotor speed of an electric wind generator is generally proportional to windspeed and is also affected by rotor power loading. Therefore, ac frequency is generally proportional to windspeed and is also affected by power loading. AC frequency is directly proportional and determines motor rpm. Centrifugal pump pressure is a direct function of rpm squared. When pumping from a well with a centrifugal pump, head or pressure is almost constant. This means that the pump must be run at some minimum rpm just to get the water to the top of the well. Also, there is a maximum rpm which the pump and pump motor can be run at due to motor construction. The result is a window of rpm at which the system can operate and pump water. Depending on components, this window may be only the upper 30 percent of the maximum windspeed the system is designed to operate in. This would mean that a system designed to start operating at 10 mph would not extract additional power from winds above 14.3 mph. If proper controls were placed on the system, the system could operate in winds above 14.3 mph but would not extract any additional power from these higher winds. The USDA-ARS Conservation and Production Research Laboratory is conducting tests which are hoped to lead to methodology for determining economical matching and operation of ac wind generators driving ac submersible pumps.

The Advanced Energy Corporation of Van Nuys, California is also developing an ac wind generator powering an ac positive displacement submersible pump (moyno type) system. For further information, Advanced Energy Corporation can be contacted at 14933 Calvert Street, Van Nuys, CA 91411, telephone (213) 732-2191.

## Electric Wind DC Generator Powering a DC Submersible Pump

The dc centrifugal submersible pumps recently introduced for use with photovoltaic panels can also be powered directly as a stand-alone water pumping system by a dc wind generator. As with an ac wind generator (see fig. 11) powering an ac submersible pump, the dc wind generator powering a dc submersible pump may be able to extract more power from the wind than the pump system used with the multiblade windmill. Also, the system may be lower in initial cost and should require less maintenance because of the use of a down hole submersible pump in place of conventional pump rods and a well cylinder.

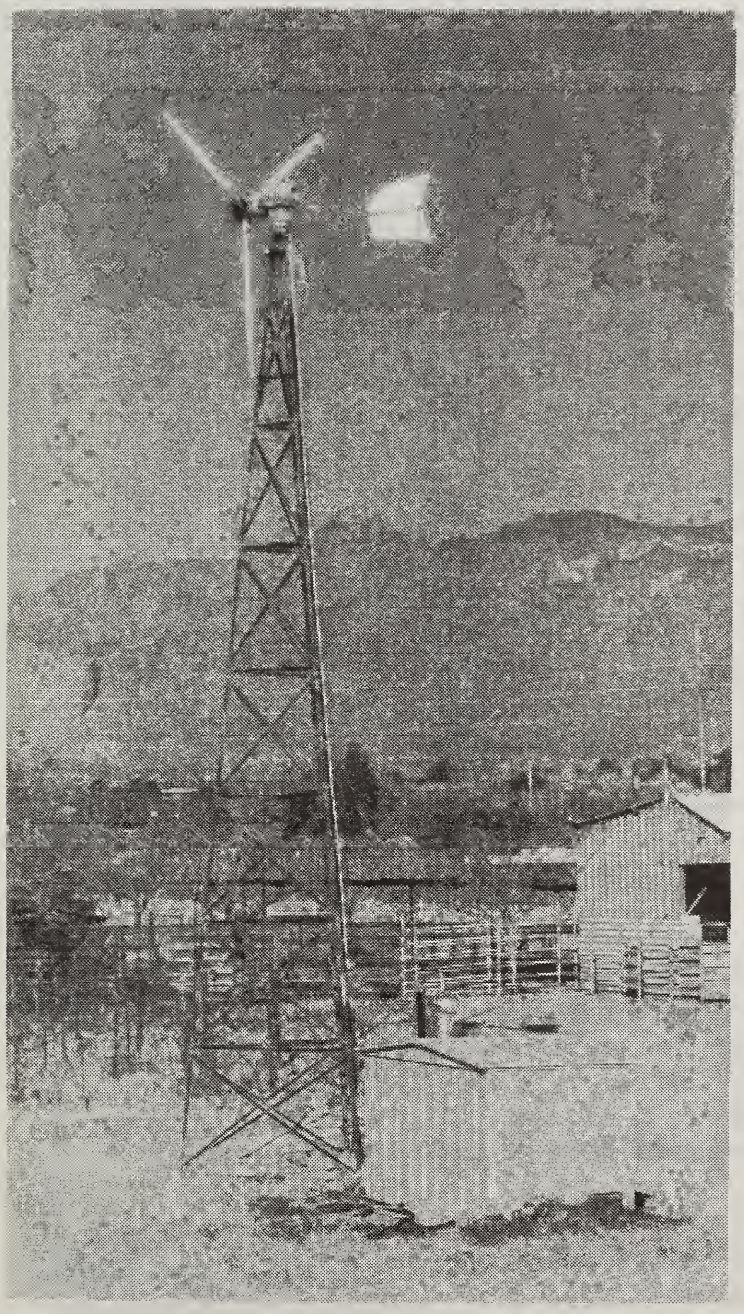


*Figure 11.—The output of an ac wind generator rectified to dc can be used to power a dc submersible pump.*

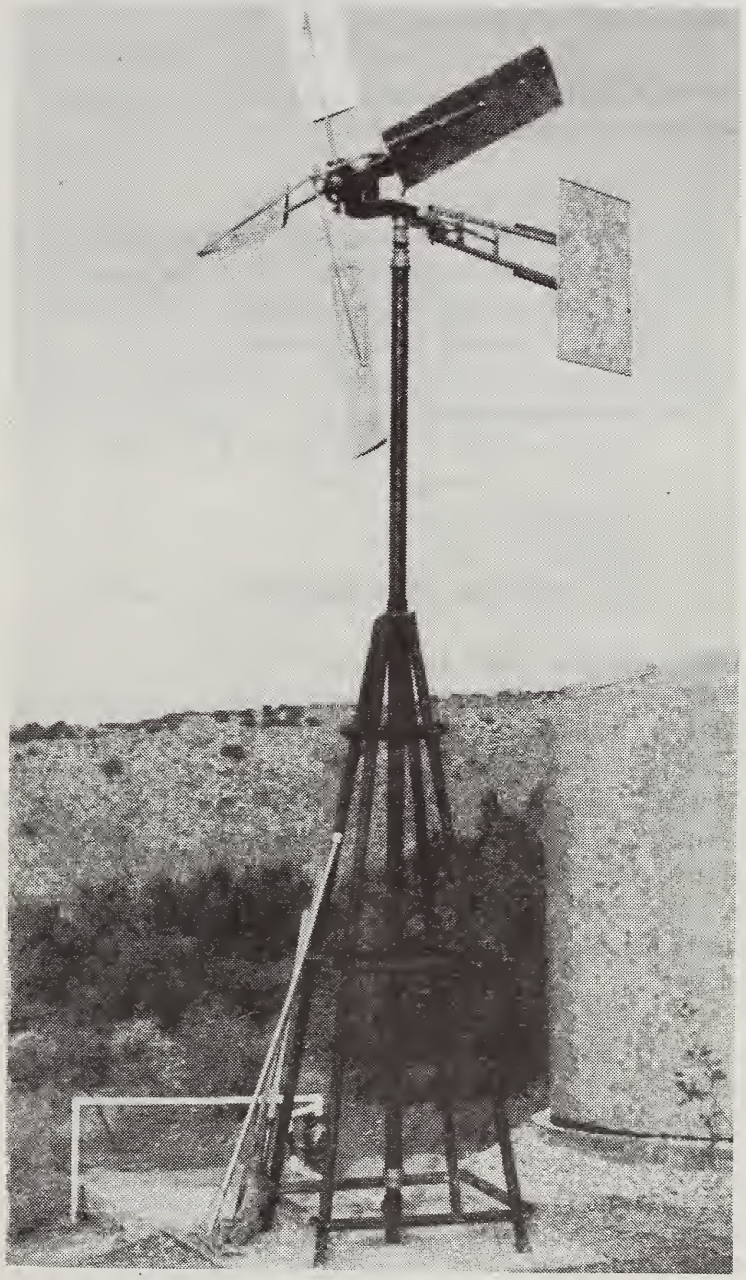


*Figure 12.—Windmill-driven air compressor which operates an air lift pump.*

Components to assemble a dc electric wind generator driving a dc submersible pump are commercially available; however, methodology for matching components is not understood, or available.

## Windmill-Driven Air Compressor Operating an Air Lift Pump

In a windmill-driven air compressor operating an air lift pump, the air compressor is driven directly by the windmill (see fig. 12). A hose carries the compressed air to the "air lift pump." The air lift pump is located below the surface of the water at least the same depth as the water is to be lifted. The air lift pump is actually just a perforated foot piece attached at the end of the drop pipe into which air is

discharged. As air is discharged into the foot piece, the water column becomes less dense and is forced up by the denser water on the outside of the drop pipe.

Windmill-driven air compressors operating an air lift pump are produced by the following:

**Pac III (Bowjon)**
700 N. Henry Ford Avenue
Wilmington, CA 90744
*Telephone:* (818) 846-2620 or
(213) 830-5520

Massey Enterprises
P. O. Box 1299
RR No. 1—Springpoint Road
Fort MacLeod, Alberta,
Canada T0L 020
*Telephone:* (403) 553-3552

## Long-Life Well Cylinder

One maintenance problem with conventional windmills is the failure of the leathers in the pump cylinder. Life of the leathers has been reported as short as 1 day, and as long as 10 years with a usual life of 6 months to 2 years. When a windmill stops pumping and the pump is in water, the failure of the leathers is generally the problem. They have to be replaced by pulling the rods and traveling valve in an open top cylinder or the rods and drop pipe in a closed top cylinder.

Longer life cylinders are available which extend the time between cylinder pump service, a reported five to six times. These pumps have closely fitting, long plungers in a steel barrel. This is the type of pump used in oil wells. These long-life cylinders are available in two designs—rod pump and tubing pump (see fig. 13). The rod pump is designed so it can be installed and removed from the well as a complete unit, including barrel, without pulling the drop pipe. The rod pump is attached to the rod end, run into the well, and is anchored at the bottom of the well by a seating nipple attached to the drop pipe. Original installations generally require the pulling of the drop pipe to attach the seating nipple. A rod-type pump can sometimes be installed without pulling the drop pipe if the rod-type pump is to replace an already installed open top conventional well cylinder. To do this, the traveling valve with leathers and the standing valve of the conventional well cylinder must be removed, leaving the conventional well cylinder in place. By placing seating cups on the bottom of the rod-type pump, running it into the drop pipe and seating it into the standing valve seat of the conventional well cylinder, the rod-type pump can be installed. Before attempting to install a rod-type pump to replace an already installed conventional well cylinder pump without pulling the drop pipe, be sure the rod-type pump will fit into a conventional cylinder barrel; and that the seating cups will fit into and seal the bottom of the pump. After installation, be sure to make a permanent record of what was installed.

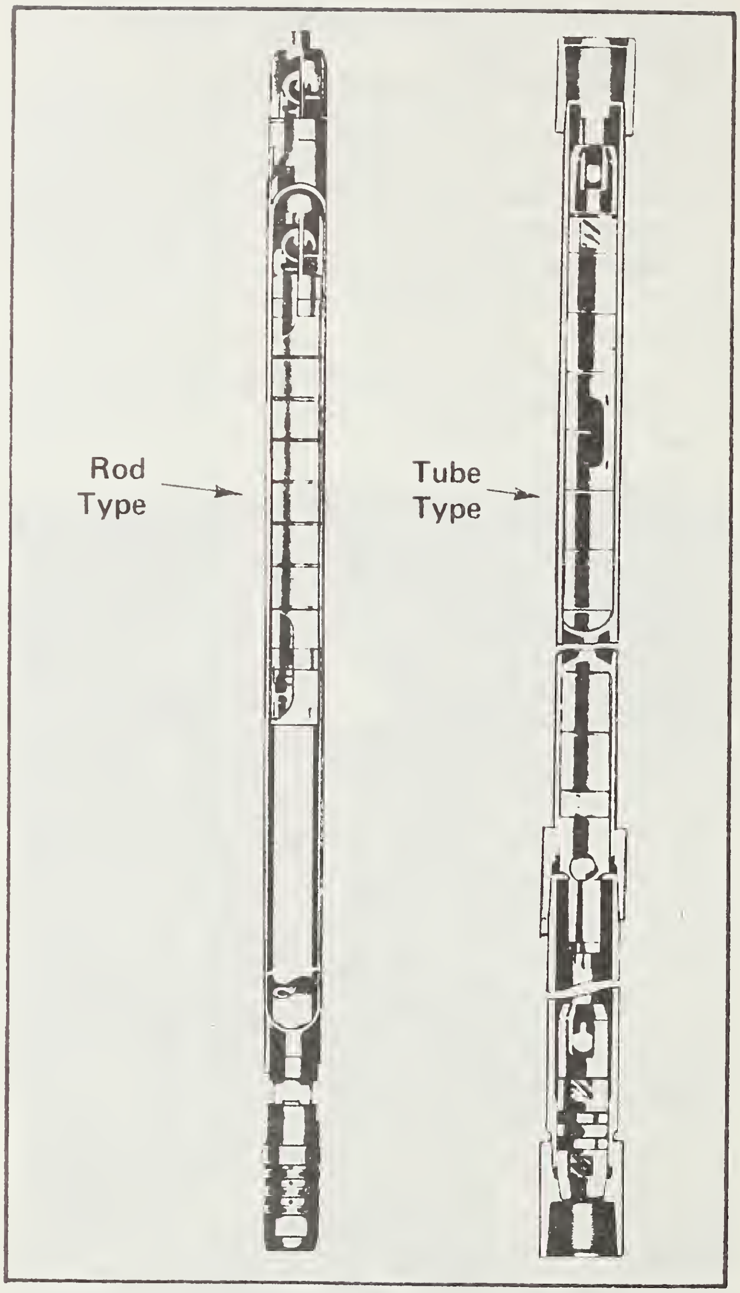



*Figure 13.—Section view of long-life cylinders.*

In the tubing-type pump, the cylinder barrel with the built-in standing valve seat is attached to the bottom of the drop pipe and the drop pipe run in. The standing valve is dropped in.

The plunger and traveling valve are then attached to the rod end and run in. The lower valve or standing valve of a tube-type pump can be pulled with the plunger and traveling valve by letting the plunger down onto the lower valve, screwing the bottom of the plunger onto the lower valve, and pulling the rods, just as with a conventional well cylinder pump.

In both the rod-type pump and tube-type pump, the work of pumping or lifting water is done on the upstroke as with a conventional well cylinder pump. With the rod-type pump, there is a common misconception that this pump pumps on the downstroke. This is because when the pump is placed in a bucket of water and operated, the rod pump will discharge water on the downstroke "proving that it pumps on the downstroke." This "proof" is not correct, because if one places the rod pump in a short piece of drop pipe, attaches a short piece of pump rod, and then places the complete unit in a bucket of water and operates the pump rod, one will find that the rod pump lifts and discharges most of the water on the upstroke. The reason it appeared that the rod-type pump pumped on the downstroke is because the "proof" was conducted using an incomplete pump.

One disadvantage of the long-life well cylinders is initial cost. The cost is three to seven times the cost of conventional well cylinders.

Long-life cylinders are available from:

**Dover Corporation/Norris Division**
P. O. Box 2070
Tulsa, OK 74101
*Telephone:* **(918) 584-4241**

**Harbison-Fisher**
P. O. Box 2477
Fort Worth, TX 76113
*Telephone:* **(817) 297-2211**

## Performance Modeling and Testing of Windmills

Despite the fact that water pumping windmills have been in production and operated for over 125 years, performance modeling and testing of windmills is being carried out with new information developed. Some of these are:

1. Evaluation of small-scale wind turbines, Alberta, Canada.

2. Windmill performance modeling by VITA (Volunteers in Technical Assistance).

3. Performance testing of horizontal axis wind turbines for the direct drive of water pumps by the University of Calgary, Calgary, Alberta, Canada.

4. Well simulator developed by Wind Baron Corporation.

### Evaluation of Small-Scale Wind Turbines

The Alberta Research Council, Edmondton, Alberta, Canada, is coordinating sponsors of a study to evaluate and demonstrate the potential of using existing wind turbines to pump water efficiently and economically under Alberta's climatic conditions. A budget of $375,000 has been provided for this 3-year study.

Six wind turbines were chosen for test. They are:

1. Dempster 14-ft multiblade with piston pump
2. Wind Baron 21-ft multiblade with piston pump
3. Bowjon 8-ft, six-blade with air lift pump
4. Windcharger 14-ft, two-blade with electric pump
5. Wilks-cam 12-ft multiblade with piston pump
6. Maverick 12-ft, three-blade with air lift pump.

Testing is planned to be completed in March of 1985.

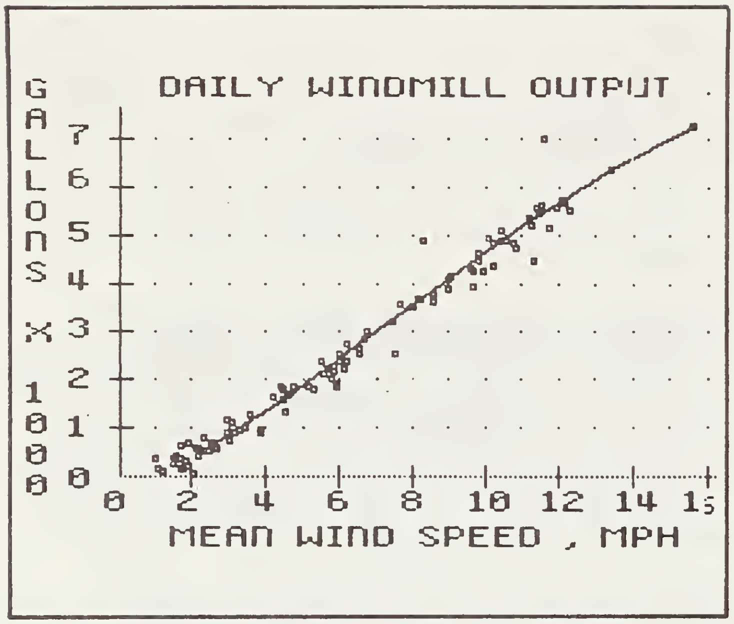
### Windmill Performance Modeling by VITA

VITA is developing computer programs which will predict the performance of water-pumping windmills. By knowing the mean wind speed for the day, and the characteristics of the windmill and site, the programs will predict the windmill output for the day (see fig. 14).

VITA is also developing a life-cycle cost computer model program to calculate the cost of each cubic meter of water pumped over the life of the windmill. Inputs for the program include windmill life, total initial capital investment, operating and maintenance costs, daily water output (obtained from the computer program which predicts performance of water-pumping windmills), salvage value, discount rate, and length of project.

### Well Simulator Developed by Wind Baron

Wind Baron Corporation of Phoenix, AZ, has developed a well simulator that can be attached to the bottom of a windmill tower (see figs. 15 and 16). This simulator can




*Explanation:* The computer program developed by VITA produced the curve in this graph to predict the water output of a 14-ft Dempster windmill with a 56-ft head, a 3-in pump, and a 10-in stroke. The dots are actual performance data recorded in Gravel Bay, Honduras, with a windmill operating at these specifications. As can be seen, the curve corresponds to actual output with considerable accuracy. VITA used an Apple II Plus microcomputer system to create this program and drawing.

*Figure 14.—Predicted (line) from VITA computer program and actual (dots) output of a windmill.*

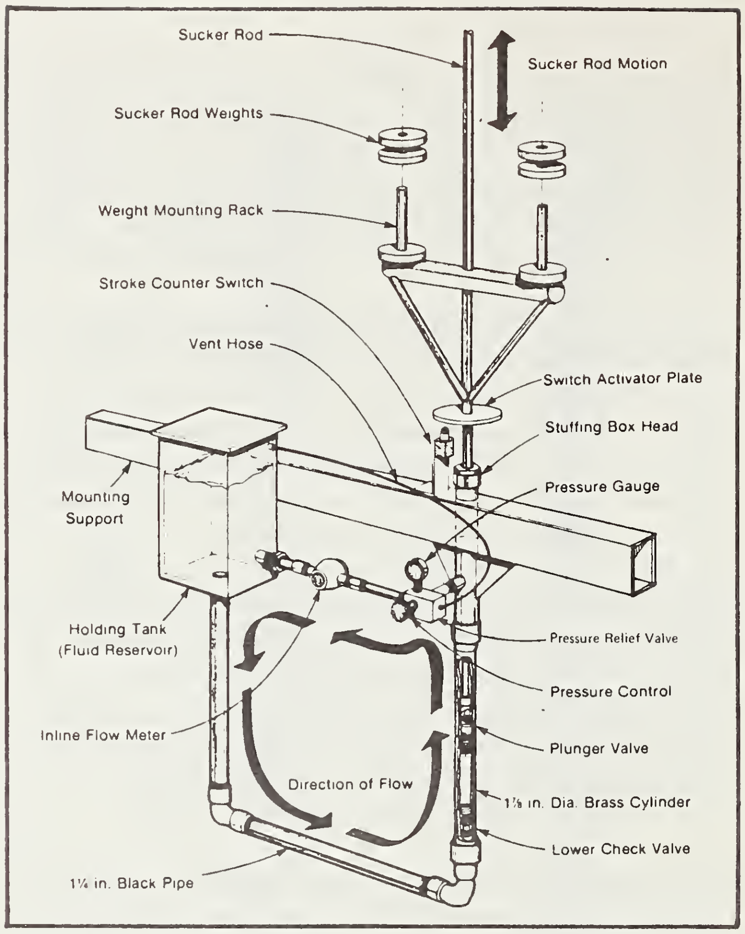



*Figure 15.—Well simulator developed by Wind Baron Corporation for windmill performance testing.*

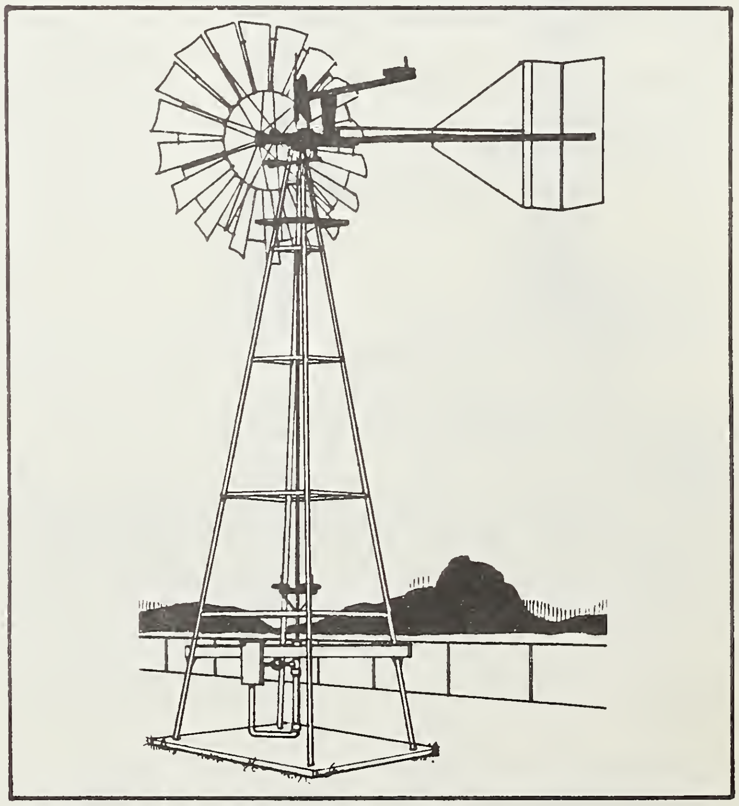


*Figure 16.—Well simulator in place on a windmill. With the well simulator, windmill performance testing at various simulated water depths can be accomplished.*

be used to test the windmill performance at any simulated well depth without the need for a well. When using this well simulator, sucker-rod weight is simulated by placing weights on a mounting rack attached to the pump pole or red rod. A standard pump cylinder forces water through an adjustable pressure-relief valve during the upstroke, simulating water load or depth. By adding weights and adjusting the pressure-relief valve, any reasonable well depth can be simulated.

## Performance Testing of Horizontal Axis Wind Turbines for Direct Drive of Water Pumps

The University of Calgary, Calgary, Alberta, Canada, is conducting performance testing of wind-turbine wheels used on water-pumping windmills. A number of reports have been issued. This work is under the direction of Professor J. A. C. Kentfield, Department of Mechanical Engineering. In one of his tests, he duplicated a wheel used by Thomas Perry (of the Perry Wheel) in his 1883 windmill tests. Professor Kentfield's test results using modern windtunnel equipment and instrumentation were the same as Perry's using an open room, a powered, revolving horizontal arm, a prony brake, and strings. Perry's accurate tests, confirmed 100 years later (to the year) by Kentfield,

must be considered an extraordinary engineering feat. And indeed it was, as Perry's work was done for the United States Wind Engine and Pump Company of Batavia, IL, which declined to use Perry's results so, in 1888, Perry, with LaVerne Noyes, formed the Aermotor Company and began to manufacture his scientifically-designed steel windmill wheel known as the Perry wheel. Almost all multiblade water-pumping windmills seen in operation today use the Perry wheel.

## PHOTOVOLTAIC-POWERED WATER PUMPING SYSTEMS

### Introduction

In the last several years, the cost of photovoltaic (solar cells) has decreased, to a level where they can be cost-effective on selected small-scale rangeland water pumping systems. In 1973, the first terrestrial solar cells were introduced. The cost of these terrestrial solar cells were approximately $50.00 per watt as compared to $2,000.00 per watt for solar cells that were being used in space. By 1978, the cost of solar cells had dropped to $20.00 per watt. The cost at this time is approximately $8.00 per watt.

In 1976, ARCO Solar installed their first solar cell powered range water pumping system on the Isleta Indian Reservation south of Albuquerque, NM (see fig. 17). This system pumps approximately 4 to 5 gallons per minute, from 213 ft,

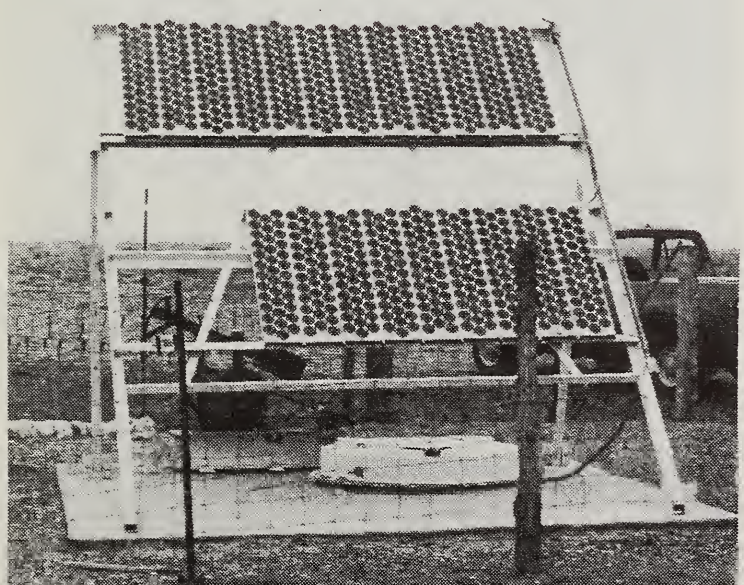


*Figure 17.—Solar cell powered water pumping system on the Isleta Indian Reservation, south of Albuquerque, NM. This system pumps 4 to 5 gallons a minute from 213 ft.*

powered by a ½-hp dc motor driving Jensen 19-W-12 pump jack. This system has 614 watts of installed solar cells and six 12-volt batteries. Total cost of solar cells, batteries, and pumping equipment was $14,000.00, most of the cost was for the solar cells.

Since this installation, many solar powered water pumping systems have been designed and installed. At the time of the installation of the Isleta unit, it was thought that a solar powered pumping system for a deep well would have to use a volumetric type "jack" pump and the installation would require batteries to supply the high current required for starting a jack pump. The reason a volumetric pump was thought to be necessary is because volumetric pumps are more efficient at the low flows found in range water pumping systems and can easily operate to depths of several hundred feet. They can also be operated by a dc motor located on the surface. Submersible pumps available at the time of the Isleta installation required ac motors. While volumetric pumps have remained more efficient at low flows, batteries have not been found to be necessary in the operation of volumetric pumps. DC submersible pump motors have been developed and methods of directly driving ac submersible pump motors from dc solar cells without using batteries have been developed.

The elimination of the requirement for batteries in a rangeland solar water pumping system was a desirable development because it costs less to store water than electricity. Terrance Paul, in his book, *How to Design an Independent Power System*, points out:

> "Batteries are a major cost component in any independent power system. Indeed in typical wind, photovoltaic or hydro systems, over the long haul, they are *the most* expensive component. For batteries not only cost a lot initially, they wear out."

Therefore, it is desirable not to have batteries in water-pumping systems, if possible.

Photovoltaic powered conventional rod and well cylinder pumps have been designed and operated without batteries. Three systems that can power photovoltaic pumping systems without batteries are: (1) large or oversized solar arrays (2) series-parallel photovoltaic panel switching, and (3) maximum power controller systems. To understand how positive displacement photovoltaic-powered pumping systems can be operated without batteries, the following information is necessary:

Conventional rod and well cylinder pumps are positive displacement type pumps that require a starting torque approximately equal to the maximum torque level when running. Torque of a dc electric motor is approximately proportional to current or amperage. The speed of a dc motor, when adequate amperage is available, is approximately proportional to voltage. The output power (hp) of a dc electric motor is directly proportional to speed (rpm) times torque. Because speed is approximately proportional to voltage and torque is proportional to amperage, power output of a dc electric motor will be approximately proportional to voltage times amperage. Therefore, changing voltage and/or amperage will result in changes in rpm, torque, and output power. The amperage output of a photovoltaic module is approximately proportional to solar radiation intensity. The voltage output of photovoltaic modules is almost constant with only a small increase as solar radiation increases. Therefore, to operate a positive displacement type pump, a system must be used that supplies adequate amperage to the motor to overcome the approximately constant torque of the pump, both starting and running. The three methods listed above are designed to do this.

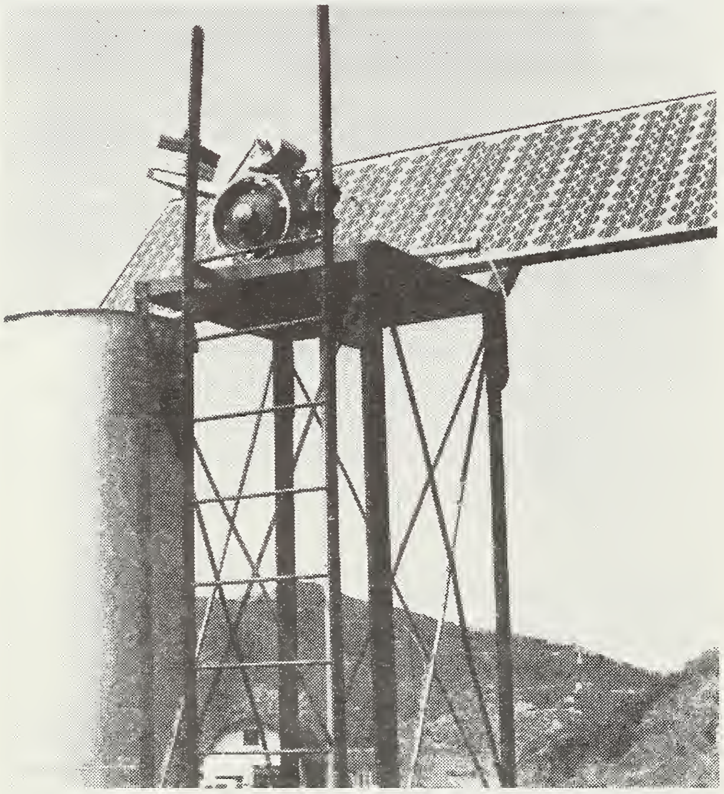
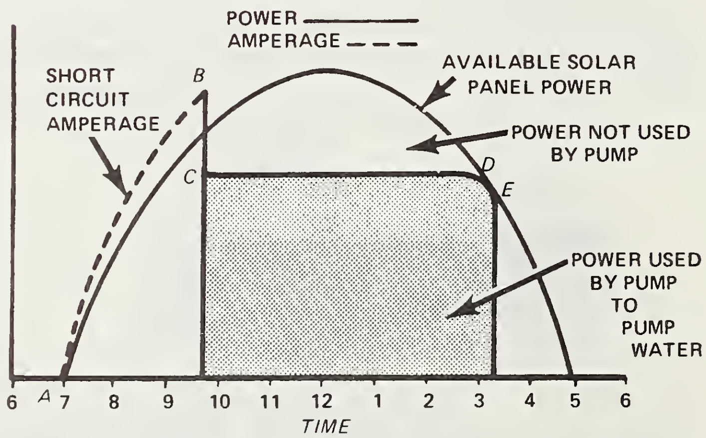


*Figure 18.—Photovoltaic solar powered conventional rod and well cylinder pump using no batteries and no controller, operating on the principle of an oversized array, near Redlands, CA. The unit pumps 2 to 3 gallons a minute from 230 ft, 5 to 7 hr a day.*

## Large or Oversized Solar Arrays

For a large or oversized solar array system, the power rating at solar noon of the panels, or array, is much larger than the power required to run the pump motor. This method of operating water-pumping systems without batteries is very simple to hook up. All that is required are the photovoltaic panels and the dc motor. Because at solar noon considerable available power that cannot be used by the dc motor driving the water pump is lost in this method; this method of powering a positive displacement pump when not using batteries would not be a desirable method to use for installations powering large motors. However, because of its simplicity, this method may be a very desirable method to use for powering a relatively low-power pumping system. Also, when using this method of powering a positive displacement type jack pump, correct counterbalance is very important in order to reduce the starting torque. Photovoltaic water-pumping systems using this method are marketed by the William Lamb Co., 10615 Chandler Blvd., North Hollywood, CA 91601, telephone (818) 980-6248 (see figs. 18 and 19).




*Explanation:* **The array is able to produce amperage as soon as the sun comes up at "A." Amperage increases until at "B" enough torque is developed to start the pump. Pump runs at power level "C," until solar power is limited at "D." At "D," available power becomes limited, until at "E" not enough amperage is available to run the pump. A large percent of the available electric power that the solar cells can produce is not used because the system does not run when the amperage is not high enough to start the unit, and when running cannot use all the available power.**

*Figure 19.—Diagram showing daily operating cycle of large or oversized solar array.*

## Series-Parallel Photovoltaic Panel Switching

In a series-parallel photovoltaic panel switching system, panels are divided into two equal sets. Within each set, the panels are connected in series and then each set is connected to a switching unit that will either connect the two series-wired sets of panels in parallel for combined amperage output or in series for combined voltage output. During times of low solar radiation, such as early morning or during cloud cover, the switching unit will connect the sets of panels in parallel, resulting in a high amperage and low voltage output that will start or keep the motor running, but at about half speed (see figs. 20 and 21). As with oversized solar array systems, it is also very desirable in series-parallel photovoltaic panel switching to have correct counterbalance on the pump in order to reduce starting torque. Series-parallel photovoltaic panel switching devices for operating water pump units are being marketed by GPL Industries, Inc., P. O. Box 306, La Canada, CA 91011, telephone (818) 956-6603.

## Maximum Power Controller System

A maximum power controller system will take the low

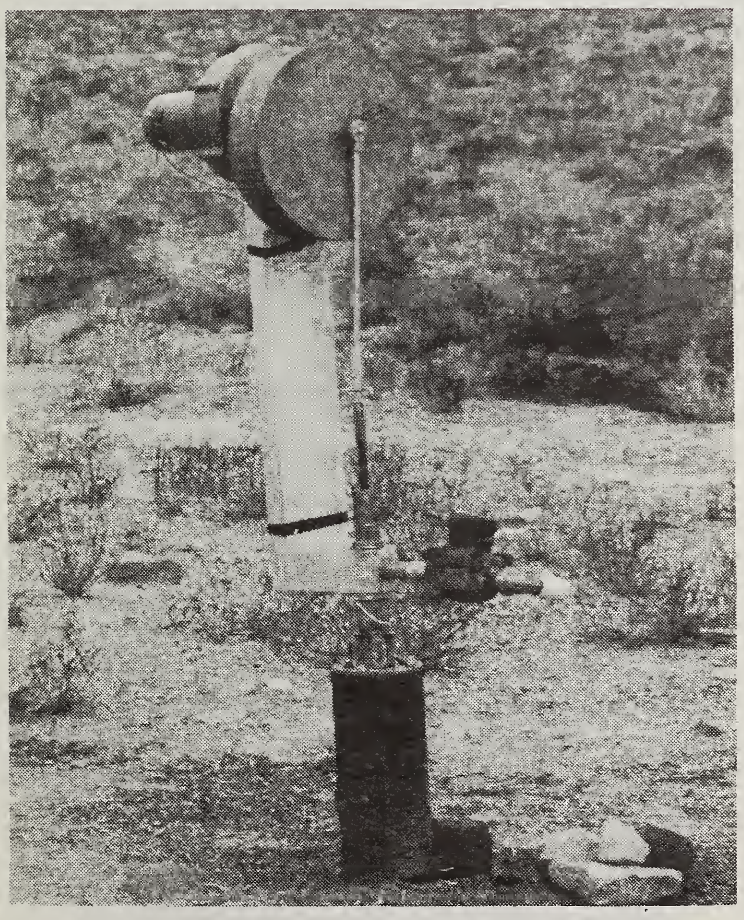
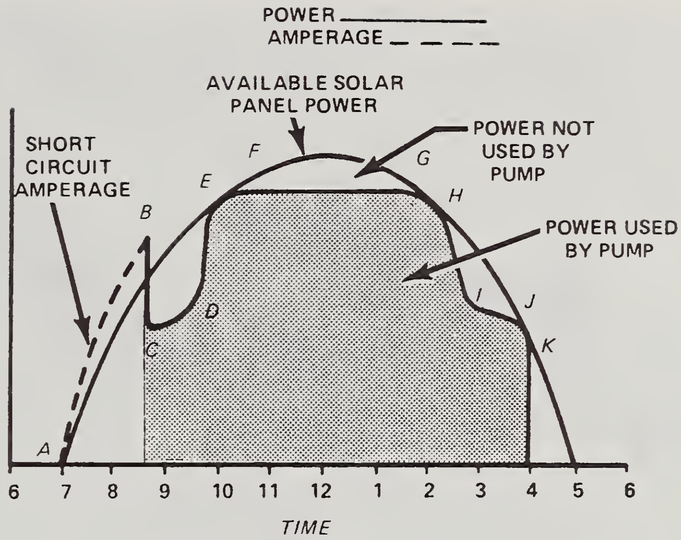


*Figure 20.—Photovoltaic solar powered rod and well cylinder pump using no batteries, operating with series-parallel photovoltaic panel switching near Carson City, NV.*




*Explanation:* **The array is able to produce amperage as soon as the sun comes up at "A." Series-parallel switch is set for parallel (combined amperage). Amperage increases until at "B" enough torque is developed to start pump. Pump starts and runs at power level "C," at about half speed. When more solar power is available, series-parallel switch is changed to series (combined voltage) and pump speed is doubled, running at "E." As more power is available, pump runs at "F" for several hours. As less power is available, pump power decreases to "H" and then series-parallel switch changes to parallel (combined amperage) and pump runs at "I" power level. As available power is reduced, pump runs at "J" and then "K," at which time there is not enough amperage to run pump. Pump stops.**

*Figure 21.—Diagram showing daily operating cycle of series-parallel photovoltaic panel switching.*

amperage and constant voltage output of photovoltaic modules just after sunrise and convert it to high amperage (enough to start and run the pump) and lower voltage (pump will run slow). As the day progresses, the photovoltaic modules will produce higher amperage and constant voltage. Then, the maximum power controller will convert this to a little higher amperage and a little lower voltage, resulting in faster motor speed and more water pumped (see figs. 22 and 23). On large photovoltaic-powered systems, at the current cost of $8 to $10 per watt for photovoltaic power, the maximum power controller system has a cost advantage. If the cost of photovoltaic power drops markedly, the maximum power controller will lose some of its advantage. As with oversized solar arrays and series-parallel panel switching pumping systems, it is also very important with maximum po[illegible]ntroller systems that a jack-type pump be correctly counterbalanced. The maximum power controller systems have been designed and marketed by:

*Figure 22.—Large maximum power controller pump jack water pumping system at Queens Well on the Papago Indian Reservation, near Tucson, AZ. This 2,700 peak watt photovoltaic-powered system pumps more than 3,200 gallons a day, from 525 ft, to supply water to a small Papago village. The system uses no batteries.*

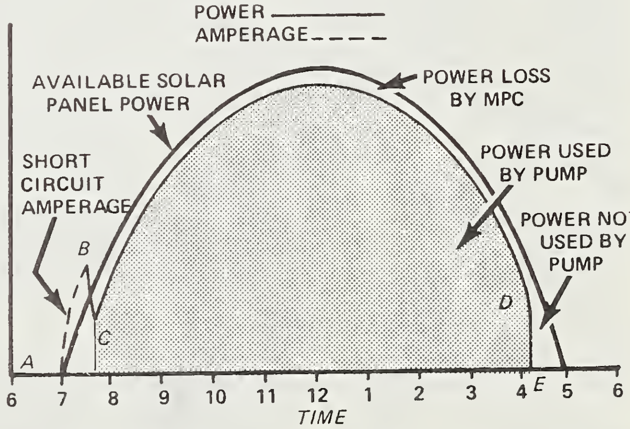
*Tri Solar Corp.*
10 De Angelo Drive
Bedford, MA 01730
*Telephone: (617) 275-1200*

*William Lamb Co.*
10615 Chandler Blvd.
North Hollywood, CA 91601
*Telephone: (818) 980-6248*

*Photocomm, Inc.*
7745 East Redfield Road
Scottsdale, AZ 85260
*Telephone: (602) 948-8003*

## Photovoltaic-Powered Pumping Systems with Submersible Pump

Manufacturers now have available water pumping systems using submersible pumps that can be powered by solar cells and require no batteries. Both dc and ac submersible pumps are available. The dc submersible pump is powered directly by the dc current from the solar cells. To power the ac submersible pump, a dc-to-ac inverter must be used. The dc-to-ac inverter, inverts the dc current to varying frequency, 3-phase ac current that powers a 3-phase ac motor at varying speeds. The dc submersible pump units are available from Jacuzzi, P.O. Box 3533, Little Rock, AR 72203, telephone




*Explanation:* The solar array is able to produce amperage as soon as the sun comes up at "A." Amperage produced by panels increases and is also increased by maximum power controller until at "B" enough torque is developed to start pump. Pump starts and runs slowly at "C." When more solar power is available, higher voltage is provided to the pump motor and it runs faster. After noon, when less solar power is available, the voltage is reduced and the motor runs slower until at "D" there is not enough power to operate the pump and the pump stops.

*Figure 23.—Diagram showing daily operating cycle of maximum power controller.*

(501) 455-1234, and A.Y. McDonald, P.O. Box 508, Dubuque, IA 52001, telephone (319) 583-7311. The ac submersible pump unit is available from Grundfos, 2555 Clovis Ave., Clovis, CA 93612, telephone (209) 299-9741.

## Determining Pump Cylinder Efficiency by Counterbalancing

When designing and installing photovoltaic water pumping systems using volumetric-type "jack" pumps, it is very desirable to have the electric motor do half the work on the upstroke and half on the downstroke. This is made possible by placing weight (counterweights) on the end of the walking beam so that when the single-acting pump is pumping on the upstroke, counterweights are being lowered supplying approximately half of the work to pump the water. To determine if the counterweight is correct, attach an ammeter to the electric motor driving the pump. If the upstroke amperage is equal to the downstroke amperage, the counterbalance weight is correct. If the amperages of the upstroke and downstroke are not equal, the counterweights can be adjusted by adding or removing weights until the upstroke and downstroke amperage is equal.

Counterbalancing in a photovoltaic-powered water pumping system can be very important. Proper counterbalancing can reduce the starting torque of a "jack" pump by up to two-thirds or more. This is important, as torque of a dc electric motor is approximately proportional to current or amperage. In a photovoltaic-powered pumping system without batteries, keeping the amperage as low and steady as possible is important.

The following items have an effect on the counterbalance:

1. Depth of water (lift)
2. Pump cylinder diameter
3. Pump rod and moving parts of cylinder weight when in water
4. Volumetric efficiency of pump cylinder (Veff)
5. Mechanical (force) efficiency of pump cylinder (Feff)
6. Overall efficiency of pump cylinder (Oeff)

*Note:* **Overall efficiency = Volumetric efficiency x Mechanical efficiency**

7. Distance from fulcrum of walking beam to center of gravity of counterbalance weights (see fig. 24)
8. Distance from fulcrum of walking beam to center line of pump rod (see fig. 24)
9. Percent of time for the upstroke and downstroke.

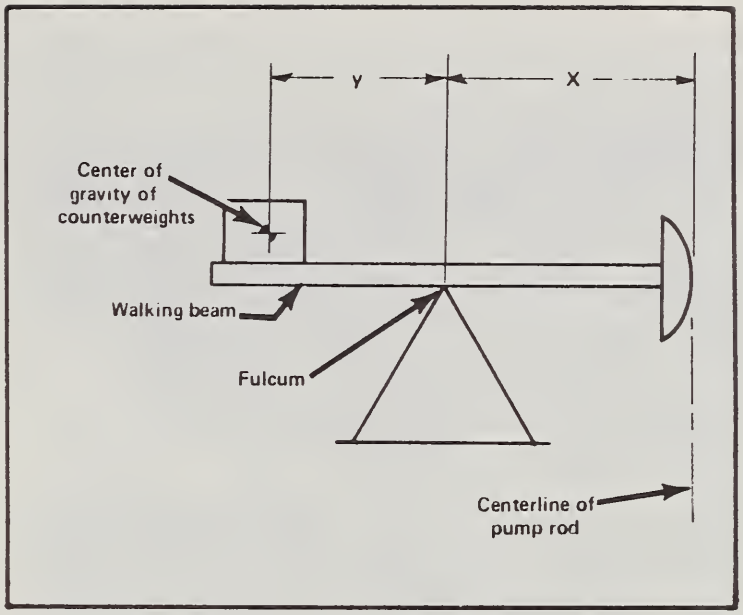



*Figure 24.—Volumetric type "jack" pump showing relationship of counterbalance weight and pump rod centerline to walking beam fulcrum.*

The theoretical counterbalance weight not considering efficiencies and rod weight is one-half the water load.

$$TC = \frac{(CA)\ (Lift)\ (.433)}{2} \qquad (1)$$

Where

TC = Theoretical counterbalance (rod weight not included)
CA = Cylinder area ($in^2$)
Lift = Water lift in ft
.433 = Change pressure from ft head to psi.

The theoretical counterbalance weight not considering efficiencies but considering pump rod weight is one-half the water load plus all of the rod weight or:

$$TC' = \frac{(CA)\ (Lift)\ (.433)}{2} + RW \qquad (2)$$

Where

TC' = Theoretical counterbalance (rod weight included)
RW = Rod and moving parts of the cylinder weight (in water) (lb)

The actual counterbalance required is the counterbalance weight required when considering efficiencies and equal to:

$$AC' = \frac{(TC' - RW)\ Veff}{Oeff} + RW$$

$$= \frac{(CA)\ (Lift)\ (.433)\ Veff}{2\ Oeff} + RW \qquad (3)$$

Where

| | | |
|---|---|---|
| AC′ | = | Actual counterbalance required (rod weight included) |
| Veff | = | Volumetric efficiency (approximately 90 percent) |
| Oeff | = | Overall efficiency of cylinder (approximately 60 to 65 percent). |

If knowing the cylinder efficiencies (Veff, Feff, and Oeff) the actual counterbalance weight can be found, for:

$$\text{Oeff} = \text{Feff} \times \text{Veff} = \frac{\text{Work out}}{\text{Work in}}$$

Feff = Mechanical or force efficiency.

Not considering rod weight

$$\text{AC} = \text{C (W + F)}$$
$$\text{TC} = \text{C (W)}$$

Where

| | | |
|---|---|---|
| TC | = | Theoretical counterbalance not including rod weight (RW) |
| AC | = | Actual counterbalance not including rod weight (RW) |
| W | = | Weight of water in standpipe on cylinder piston area |
| F | = | Friction force to move cylinder |
| C | = | Constant |

$$\text{Feff} = \frac{\text{C (W)}}{\text{C (W + F)}} = \frac{\text{TC}}{\text{AC}} = \frac{\text{Oeff}}{\text{Veff}}$$

$$\text{AC} = \frac{\text{TC Veff}}{\text{Oeff}}\ ^{*} \qquad (4)$$

Also

$$\text{Oeff} = \frac{\text{TC Veff}}{\text{AC}} \qquad (5)$$

***NOTE: Rod and moving cylinder weight not considered and must be added in a real world problem.**

$$\text{AC}' = \frac{\text{TC Veff}}{\text{Oeff}} + \text{RW} \qquad (6)$$

In the development of this method of determining cylinder efficiencies by knowing counterbalance weight, or predicting (determining) counterbalance weight knowing cylinder efficiencies, one item has not been used and that is the percent of time for the upstroke and the downstroke. On many small pump jacks and almost all windmills, the time for the upstroke is longer than the time for the downstroke. The relation to the required counterbalance weight is as follows:

$$\text{AC}'' = \text{AC}\ \frac{\text{DT}}{\tfrac{1}{2}\text{T}}$$

| | | |
|---|---|---|
| AC″ | = | Actual counterbalance required when accounting for percent of time for the up- and downstroke (rod weight not included) |
| T | = | Total stroke time |
| DT | = | Downstroke time |
| $\frac{\text{DT}}{\text{T}}$ | = | DS % |
| DS % | = | Downstroke percent of time |

Then

$$\text{AC}'' = \text{AC 2 (DS \%)}$$

**NOTE: Rod or moving pump part not considered. Rod or moving pump part added in.**

Then

$$\text{AC}''' = \text{AC 2 (DS \%) Veff + RW}$$

$$\text{AC}''' = \frac{\text{2TC (DS \%) Veff}}{\text{Oeff}} + \text{RW} \qquad \text{from (4)}$$

$$\text{AC}''' = \frac{2(\tfrac{1}{2})\ (.433)\ (\text{CA})\ (\text{Lift})\ (\text{DS \%})\ \text{Veff} + \text{RW}}{\text{Oeff}} \qquad \text{from (1)}$$

$$\text{AC}''' = \frac{(.433)\ (\text{CA})\ (\text{Lift})\ (\text{DS \%})\ \text{Veff}}{\text{Oeff}} + \text{RW} \qquad (7)$$

When considering the distance from the fulcrum of the walking beam to the centerline of the pump rod (x), and the distance from the fulcrum of the walking beam to the center of gravity of counterweights (y) (see fig. 24), actual counterbalance (AC″″) becomes:

$$\text{AC}'''' = \frac{(.433)\ (\text{CA})\ (\text{Lift})\ (\text{DS \%})\ \text{Veff}\,(x)}{\text{Oeff}\ (y)} + \frac{X}{y}\ \text{RW}$$

The volumetric efficiency can be determined by tests and, for a well cylinder pump in good condition, the volumetric efficiency has been found to be approximately 90 percent. If an installation is made and the correct counterbalance weight is found by making upstroke and downstroke

amperage equal, the overall efficiency of the well cylinder can be determined. Overall efficiency of one well cylinder operating at 110 ft has been found to be 58 percent by strain gaging the polish rod. (This test validated determining overall efficiency and mechanical efficiency by counter-balancing.) The overall efficiency of a well cylinder may vary considerably over depth and with manufacturer.

If overall efficiency of a well cylinder is known, the actual counterbalance weight required can be predicted. The benefits of being able to predict the correct counterbalance weight are: The correct size of pump jack can be selected and ordered, the correct number and size of counterweights can be ordered, and if the counterweight needed is not the counterweight predicted, there probably is a problem.

### Solar-Thermal Pumping Systems

In the World Bank's report *Small-Scale Solar-Powered Irrigation Pumping Systems, Technical and Economic Review,* September 1981, dealing with solar-thermal power systems, they state: "Despite the long history (solar-thermal water pumping systems were operating in 1903) of solar-thermal powered systems, there are still no manufacturers producing systems on a commercial basis in the world market. In the consultant's opinion (Sir William Halcrow and Partners/Intermediate Technology Power, Ltd.), none of the systems currently available are as yet sufficiently developed to be viable in comparison with many other energy conversion systems under free market conditions. Nevertheless, there are a number of prototype devices that could possibly offer prospects for development into viable pumping systems." (See figs. 25 and 26.)

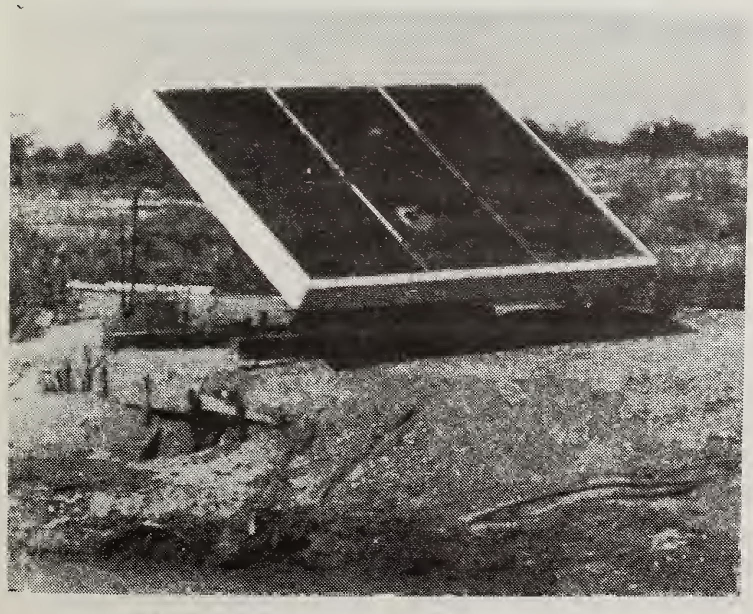


*Figure 25.—Solar-thermal water pumping system operating near Tucson, AZ.*

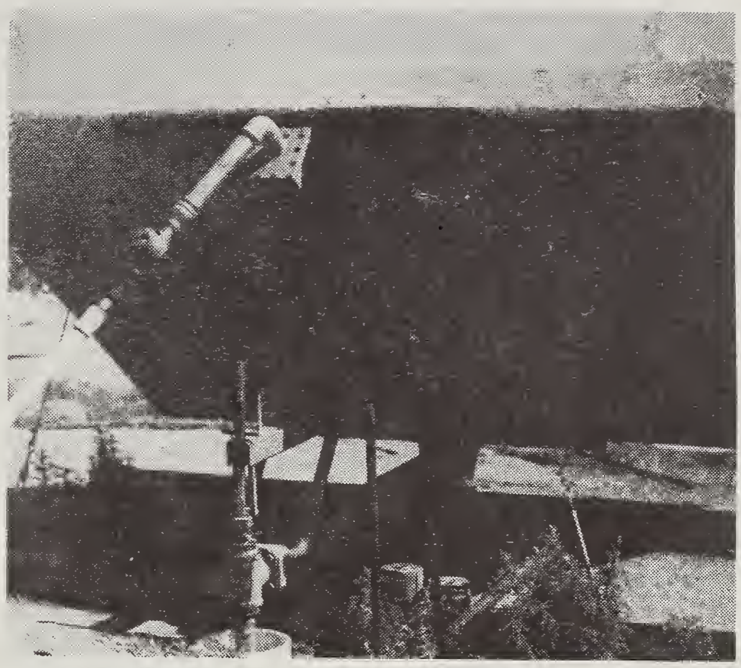


*Figure 26.—Rear view of solar-thermal water-pumping system.*

## USEFUL PUBLICATIONS ON WATER WELL SYSTEMS

During this investigation, a number of very good books and other publications on water wells, water well pumping, pumps, use of solar energy, and electricity were located. The following is a list of the most noteworthy.

*Water Well Handbook*
by Keith E. Anderson

Available from:

Missouri Water Well and Pump Contractors Assn.,Inc.
P. O. Box 517
Belle, MO 65013
*Telephone:* (314) 859-6505

Cost: $10.00

A very complete and well done handbook on water wells. The text covers mathematical formulas and conversion tables, water data, quality of water, cable tool drilling, rotary drilling, air rotary drilling, pipe and casing, pumps, electrical data, flow measurement, geology and hydraulics of wells, water supply and equipment, and windmills.

*Planning for an Individual Water System*

Available from:

American Assoc. for Vocational
Institutional Materials (AAVIM)
Engineering Center

Athens, GA 30602
Telephone: (404) 542-2586

Cost: $6.95

A very good book on how to plan a safe and adequate water supply. This text was developed for the person who has the responsibility of providing a water system for a suburban home, vacation home, farm, or ranch. Anyone who depends on an individual water supply will find this book valuable because it will help them to understand the many factors involved in designing, selecting, using, and maintaining small size water systems.

Other useful water well and water systems texts are:

*Private Water Systems Handbook*

Midwest Plan Service
Iowa State University
Ames, IA 50011
*Telephone:* (515) 294-4337

Cost: $4.00

*Water Systems Handbook*

Water Systems Council
221 North La Salle Street
Chicago, IL 60601
*Telephone:* (312) 346-1600

Cost: $6.00

***Useful Publications on Windmills:***

*A Performance Model for Multiblade Water Pumping Windmills*
by Alan S. Wyatt and Jonathan Hodgkin

Available from:

Volunteers in Technical Assistance (VITA)
P. O. Box 12438
Arlington, VA 22209-8438
Telephone: (703) 276-1800

An excellent engineering analysis of the principles of operation of a multiblade water pumping windmill. This paper is written for the engineer and should be expanded to increase a broader understanding; however, it is an excellent base.

*High Output Water Pumping Windmill*
by Don Avery

Available from:

Don Avery
45-437 Akimala Street
Kaneohe, HI 96744
*Telephone:* (808) 247-1909

This report describes the development and validation testing of the automatic stroke control for conventional windmills and for a three-bladed wind turbine.

*Dempster Windmill Catalog*

Available from:

Dempster Industries, Inc.
Beatrice, NE 68310
*Telephone:* (402) 223-4026

This catalog has information on windmill selection, hand-pumps, well cylinders, submersible pumps, and pump accessories. It also has a section on basic pump principles with four leading questions to proper pump selection. This section also includes practical engineering information useful in designing water pumping systems.

*Windmills and Pumps of the Southwest*
by Dick Hays and Bill Allen

Available from:

Eakin Press
P. O. Box 23066
Austin, TX 78735

Cost: $7.95

This book begins with the basics of windmill design and operation and covers installation, troubleshooting, and repair of windmills in understandable terms. The authors discuss how to select a windmill for a specific pumping job and since most windmillers also work with power pumps, a chapter on power pump installation and repair is included. This book is written for the beginner and for the non-engineer. Engineers and very serious windmill students should also refer to Alan Wyatt and Jonathan Hodgkin's "A Performance Model for Multiblade Water Pumping Windmills" and expanded material for selection of windmills.

## USEFUL PUBLICATIONS ON PHOTOVOLTAIC WATER PUMPING

<u>*Evaluation of Pumps and Motors for Photovoltaic Water Pumping Systems*</u>
by David Waddington and A. Herievich

Available from:

Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401

An excellent report describing tests on pumps powered by photovoltaic cells. This is a very informative report on powering pumps with photovoltaic cells and has a procedure for design of a water pumping system.

The World Bank project, Testing and Demonstration of Small-Scale Solar-Powered Pumping Systems, has completed and published five reports to date. The reports for the World Bank project by Sir William Halcrow and Partners, in association with the Intermediate Technology Development Group, Ltd., both of London, England are:

- *Testing and Demonstration of Small-Scale Solar-Powered Pumping Systems—A State-of-the-Art Report,* December 1979.
- *Small-Scale Solar-Powered Irrigation Pumping Systems Phase I Project Report,* July 1981.
- *Small-Scale Solar-Powered Irrigation Pumping Systems—Technical and Economic Review,* September 1981.
- *Small-Scale Solar-Powered Pumping Systems: The Technology, its Economics and Advancement,* June 1983.
- *Handbook on Solar Water Pumping,* February 1984.

A good publication on stand-alone power systems is:

<u>*How to Design and Independent Power System*</u>
by Terrance Paul

Available from:

Best Energy Systems for Tomorrow, Inc.
P. O. Box 280
Necedah, WI 54646
*Telephone:* (605) 565-7200

Cost: $4.95

This book states that batteries are a major cost component in any independent power system. "Indeed, in typical wind, photovoltaic or hydro systems, over the long haul, batteries are the most expensive component. Batteries not only cost a lot initially, they wear out."

## CONCLUSIONS

Much more range water pumping equipment is available now than when this project was started. Examples are: AC submersible pumps operating from solar cells, dc submersible pumps, and solar cell water pumping systems using jack-type pumps operating without batteries. However, many developments are not complete and technical information is not fully available.

## RECOMMENDATIONS

### Long Range

For this Long Range Water Systems Improvement project, the long range recommendation is to produce a handbook on rangeland water pumping systems.

### Short Range

A number of short range developments need to be carried out before a handbook on rangeland water pumping systems can be completed. Therefore, the short range recommendations for this project, in order of priority, are a series of different but related rangeland water system developments as follows:

- Development and implementation of an automatic stroke control for multiblade windmill.
- Development and implementation of an ac electric wind generator powering an ac submersible pump.
- Development and implementation of a dc electric wind generator powering a dc submersible pump.
- Development and implementation of an automatic stroke control for a three-bladed wind turbine.

- Assist field units in the design and installation of range solar water pumping systems.

- Assist field units in the application of VITA computer performance models for windmills.

- Collect, evaluate, and disseminate information on range water pumping testing by World Bank, Alberta Canada, Agriculture Irrigation Division; performance modeling by VITA, etc.

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